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Understanding Sedimentation Process in the Makoye Reservoir of Southern Zambia

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Abstract

Reservoir sedimentation is one of the problems facing managers of small reservoirs (with ≤5m height of embankment). The main methods used to understand sedimentation process in the Makoye reservoir included sediment coring, onsite measurements using Sedimeter SM3A, use of Elevation Change Method (EMC), laboratory analysis of sediment core, 3D Spatial Analyst Tools (3DSATs) in ArcGIS 10.3 as well as mathematical models. The reservoir had been silting at a significant rate of 3,112.97 m^3 yr^{-1} leading to average accumulation of 87,163 m^3 of sediment, which had eventually reduced the reservoir's storage capacity by 53.5%. The EMC methods also revealed that Makoye reservoir tapped 79,749.38 m^3 of sediment giving rise to the between method average sediment volume of 83,456.26 m^3. Reservoir's useful life was found to be 24 years. Results from Sedimeter SM3A showed that a total depth of 0.688cm of sediment had accumulated during a period of 309 hours in the 2015/2016 rainy season as compared to 1.56 cm in the 2016/2017 rainy season. The long term average depth of sediment was found to be 2.4 cm. It was concluded that sedimentation in the Makoye Reservoir is a serious problem which may lead to complete loss of reservoir storage capacity.

Keywords: Sedimentation rate, reservoir capacity, Sediment yield, Useful life, Sedimeter-SM3A

1. Background

Reservoir sedimentation is one of the problems facing managers of small reservoirs (with ≤5m height of embankment) (Nissen-Petersen, 2006) and, it has persisted in literature (Meade, 1982; Walling, 1988; Sichingabula, 1997; Collins and Walling, 2004; Lu *et al*., 2013; Sichingabula *et al*., 2014; Chomba and Sichingabula, 2015) such that it still needs further studies particularly in Zambia where sediment data is quite scanty. Due to very low velocity (<0.035ms^{-1}) of water in reservoirs, they tend to be very efficient sediment traps leading to untimely loss of reservoirs' useful life, storage capacity as well as reduced water quantity and quality (Lu *et al*., 2013). Rainfall, runoff and river channel erosion provide a continuous supply of sediment that is finally deposited into reservoirs, if sediment inflow is large relative to the reservoir storage capacity, then the useful life of the reservoir may be drastically shortened (Randle *et al*., 2008). Collins and Walling (2004) noted that information on sedimentation is an important data requirement for reconstructing historical catchment erosion patterns and assist in the interpretation of sediment loads in small reservoirs. Moreover, the capacity to manage current and predicted sedimentation problems depends, in part, upon an improved understanding of sediment load (Collins and Walling, 2004). This study aimed at determining quantity of sediment and rate of sedimentation in the Makoye reservoir.

2. Literature Review

2.1 Bathymetric Method of Assessing Reservoir Sedimentation

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According to Ajith (2016), the term bathymetry originally referred to the ocean's depth relative to sea level, although it has come to mean submarine topography or the water depths and shapes of underwater terrain. Bathymetry is the foundation of the science of hydrography, which measures the physical features of a water body. The bathymetric approach is based on a simple comparison of reservoirs morphology at two different time periods, first at the time of the construction of the reservoir and second, at the time of the survey, which should be at least ten years later to detect significant changes (United States Army Corp of Engineers (USACE), 2015). Bathymetric survey approach provides reservoir sedimentation details and much needed information such as reservoir depth, capacity and bottom topography with great accuracy to optimize reservoir operations. This method is mainly used to estimate the capacity of reservoir and consequently, the amount of sedimentation over time (Curtarelli *et al.,* 2015).

In his study, Ajith (2016) used Differential Global Positioning System (DGPS), Navitronic Echo-sounder (NS-415), sound velocity probe, survey-Computer to conduct bathymetric survey of the Peechi Dam at Full Reservoir Level (FRL) in Kerala area of India. Using such bathymetric tools and surfer software for analysis, Ajith (2016) concluded that Peechi Dam had lost its reservoir capacity by 14.027% of the original (79.25m depth and 110.436 million m^3 of water). This demonstrated the rate of sedimentation at 0.27 million m^3 (0.25%) per year. The actual calculated capacity was 94.946 million m^3, hence this shows an actual loss of capacity of 15.490 million m^3 in 56 years (Ajith, 2016). Bathymetric Survey of the same reservoir in 2004 showed that, its capacity was 96.414 million m^3, but as of 2016, the calculated capacity stood at 94.946 million m^3 showing a reduction by 1.468 million m^3 over a period of nine years or 0.1631 million m^3 per year from 2004 (Ajith, 2016). Other studies have employed this method, for example, McPherson *et al.* (2009) used this method to study the storage capacity in relation to sedimentation of the Loch Lomond Reservoir in California; Fernando *et al.* (1999) used it to assess sedimentation in the Laguna De Bay in the Philippines, Richard *et al.* (2000) used it to assess sedimentation on the Loch Raven and Prettyboy reservoirs in Maryland, USA. The Kansas Biological Survey (KBS) (2009) performed a bathymetric survey partly to determine sedimentation of the Clinton Reservoir in Douglas County, Kansas. Şebnem *et al.* (2009) used similar method to assess sedimentation in the Tahtali Basin in Turkey.

In Southern African context, Mavima *et al.* (2011) assessed land use impact on reservoir sedimentation during the 2009-2010 rainfall season. Using hydrographic surveys and grab sampling methods at Chesa Causeway reservoir in the Upper Ruya sub-catchment of Zimbabwe, Mavima *et al.* (2011) showed that sediment specific yields at the reservoir were 774 t $km^{-2}yr^{-1}$ (using the grab sampling method) and 503 t $km^{-2}yr^{-1}$ (using hydrographic survey). Nevertheless, the conventional methods of determining sediment fluxes such as manual hydrographic surveying and grab sampling methods do not provide accurate data because they were inherently marred with several inaccuracies. For example, the differences in sediment specific yields obtained from the two methods are arguably wide, thereby, bringing the reliability of results into question. Much as we appreciate such results, Ajith (2016) states that it requires about 10 years to accurately determine sedimentation rates using bathymetry method and tools. In a short term it is very challenging to detect what has settled on the reservoir bed. However, the current study overcame such a limitation by employing a Sedimeter SM3A which is able to measure reservoir sedimentation rates per second or minute or hour or day or month depending on one's preference. Moreover, assessing sedimentation using bathymetric survey requires use of a sonar with a very accurate GPS without which the estimation of sedimentation would be compromised. For example, the NS-415 used by Ajith (2016) had an accuracy in position of centimetres to meters which sound fairly accurate in the absence of alternatives, but a Remote Controlled-2 Hydrographic Survey Boat (RC-2HSB) would have offered higher accuracy than NS-15 because its position accuracy is in millimetres to centimetres and sometimes less than millimetres depending on satellite reception. Moreover, if different methods of bathymetric survey are used between different temporal scales, results are inaccurate. This means that the methods between different time periods must be as replicable as possible.

2.2 Sediment Coring Method

This method is useful where a reservoir dries up during part of the year especially dry season. It involves digging of accumulated sediment layers in order to determine their thickness along transect (Brunner, 2012). This is one of the methods which the KBS (2010) employed during assessment of sedimentation at Clinton Reservoir in Kansas. Sichingabula *et al.* (2014) employed this method to determine sedimentation in selected reservoirs of Southern Zambia. Brunner (2012) has documented in detail how this method works. However, it is not suitable where a reservoir does not dry during part of the year.

In such cases, sediment cores are obtained through locking sediment corers, such as beaker sampler, among others, because it can be used to collect sediment even if the reservoir contain some water. Few (2014) used such methods in the South East Greenland, whilst Peter *et al.* (2004) also used these methods in their study in the USA. Brunner (2012) has widely documented the application of these methods. Generally this method is only useful when there is no pre-impoundment map and the sediment thickness is relatively small. According to Brunner (2012), sediment coring is a site specific method as it is dependent on the accuracy of the data collection procedure.

*2.*3 Remote Sensing Method

Remote sensing is one of the methods that is receiving attention in assessment of reservoir sedimentation. There are different techniques within this method, namely, optical remote sensing from planes, radar altimetry and multi-beam sonar. The Satellite Remote Sensing (SRS) method for assessment of reservoir sedimentation is based on the fact, that, the water spread area of reservoir at various elevations keeps on decreasing due to sedimentation. These techniques have been used in various studies for example, Goel *et al.* (2002) used digital imagery processing to assess sediment deposition rate in the Bargi Reservoir, Narasayya *et al.* (2005) also used this technique to assess sedimentation in the Srisailam Reservoir located in Andhra Pradesh State of India. Light Detection and Ranging (LIDAR) is another technique that provide fairly accurate land surface altitude similar to the way an echo-sounder operates. Ceylan and Ekizoglu (2012); Lopes and Smith (2007), Jain *et al.* (2009) have used this method before. However, this method is not very suitable in places like Zambia where remote sensing data bases are not fully updated. Moreover, not all necessary details can be captured remotely, there has to be a complementary in-situ measurement to validate state of sedimentation process.

2.4 Determination of Real Time Sedimentation Rates

Most of existing literature and studies (Sichingabula 1997; 1999; Mavima *et al.* 2011; Chihombori *et al.* 2012; Bunyasi *et al.* 2013; Ajith 2016; Chomba and Sichingabula, 2015) on rates of sedimentation are based on derivative computation of other variables unlike real in-situ measurement. This implies that if the initial data from which sedimentation rates were computed had errors, the computed values would also be inaccurate. The latest study by Chomba and Sichingabula (2015) in Lusaka East, Zambia, only estimated rates of sedimentation using mathematical models and equations by Anyekulu *et al*. (2013) on annual basis. Chomba and Sichingabula (2015) found that the estimated rates of sedimentation for Silverest reservoir was 14,595.40 m^3yr^{-1} and, at this rate, the reservoir lifespan was found to be 26 years. For Lwiimba reservoir, sedimentation rate was estimated at 2,200.99 m^3yr^{-1} with chances of living up to the next 46 years; Katondwe reservoir's rate of sedimentation was at 283.92 m^3yr^{-1} with a remaining lifespan of 38 years. As for Morester reservoir, the rate of sedimentation was determined at 251.01 m^3yr^{-1} with a lifespan of 58 years. These rates of sediment deposition contributed to reservoir capacity storage losses of 99,044.57 m^3; 379,480.5 m^3; 13,805.68 m^3 and 9,937.12 m^3 for Lwiimba, Silverest, Morester and Katondwe, respectively, with the general consequence of reservoir drying up during the dry season.

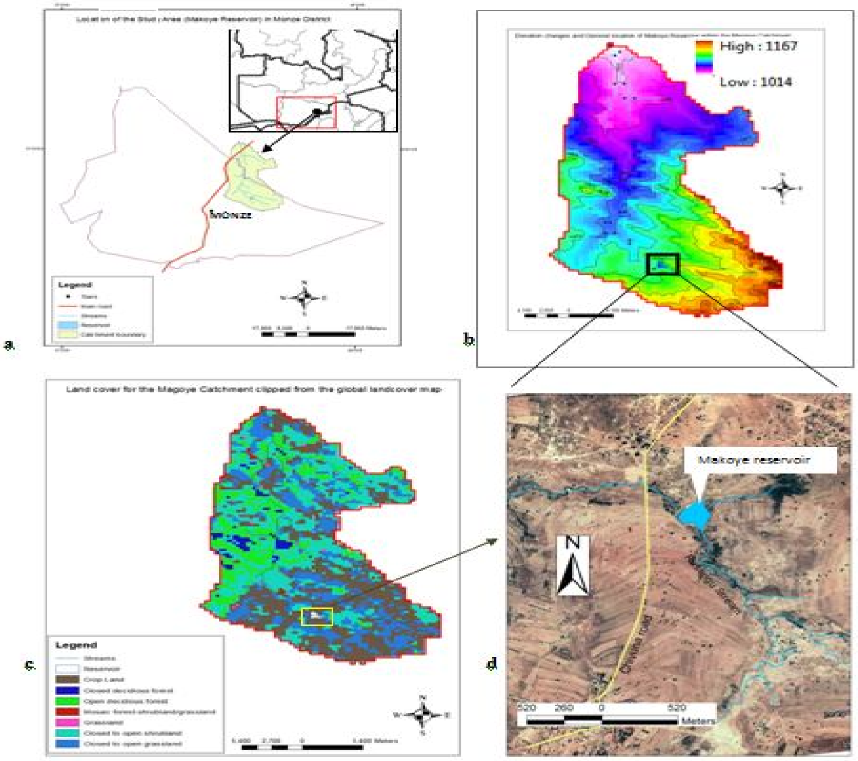
The current study did not only use derivatives, but also physically measured and determined sediment settling rate using a Sedimeter SM3A (Erlingsson, 2016). Nonetheless, the real time determination of sedimentation using Sedimeter SM3A is relatively new not only in Africa today, but also in other parts of the World. The first one was done by USACE in 2009 to measure sediment deposition over mussel beds during maintenance dredging on the Ohio River, West Virginia, in the United States of America (USA) (Erlingsson, 2016). However, it was not directly used in a reservoir environment and the results were not scientifically publicized. The second case study of real time measurement of sedimentation was recorded in Kazakhstan in the northern part of the Caspian Sea, which had a large input of sediment from the Volga and Ural rivers, reducing its depth to about 5 meters over a large area (Erlingsson, 2016). In this case study, Sedimeter was deployed only to assess real time rates of sedimentation for the Environmental, Social, and Health Impact Assessment (ESHIA) programme and, not for scientific publication (Erlingsson, 2016). The third case study was recorded in 2014 in the Washington State, north eastern part of the USA (Erlingsson, 2016). In 2007, the Port of Olympia found elevated levels of dioxins in an area scheduled for maintenance dredging. During this project, Sedimeters were deployed in the area to monitor for near-bed elevated turbidity levels and to determine for sedimentation in real time.

However, results of the project were just meant for that purpose and have not been published in a scientific journal (Erlingsson, 2016). This study is probably the first one to use the Sedimeter for understanding reservoir sedimentation process in Africa.

3. Study Area

Makoye reservoir is found in the Magoye Catchment (434.34 km^2) in Njola area, east of Monze District in southern Zambia (Figure 1a-d). It is specifically located between 16°14'08.4" South to 16°15'06.8" South and 27°40'52.8" East to 27°42'49.8" East and, has a surface area of about 76,437.11 m^2. It was built in 1940 and, it was renovated in 1988 due to minor breaching of the crest. The sub-catchment in which Makoye reservoir is located has an area of about 5 km^2. The reservoir is located in ecological Zone-IIa with mean annual rainfall of $\leq 815\ \text{mm}$ (Meteorological Department of Zambia (MDZ), 2014). Geologically, it is underlain by the Zambezian belt and, it is covered by chromic-luvisols and Orthic Ferralsols soils (Food Agriculture Organization (FAO), 2006). Southern miombo vegetation is the most common in the catchment area (Storr, 1995). Sedentary subsistence type of agriculture is its economic backbone (Central Statistical Office (CSO), 2015). The population of households in the catchment is over 474, of which 77% depend on pastoral and crop farming (CSO, 2015). According to Ministry of Livestock and Fisheries (MLF) (2016), there are over 10,000 heads of cattle that depend on the Makoye reservoir. Makoye reservoir was selected because it is one of the reservoirs that experiences huge problem of sedimentation, and it is also a source of domestic and livestock water during most parts of the year. Figure 1 shows the study area.

Figure 1: (a) General location of the Makoye Reservoir in Monze District, (b) Delineated Magoye Catchment based on global DEM, (c) Land cover/use for the Magoye Catchment (d)Immediate catchment of Makoye Reservoir



4. Methodology

4.1 Reservoir Sampling Process and Selection Criteria

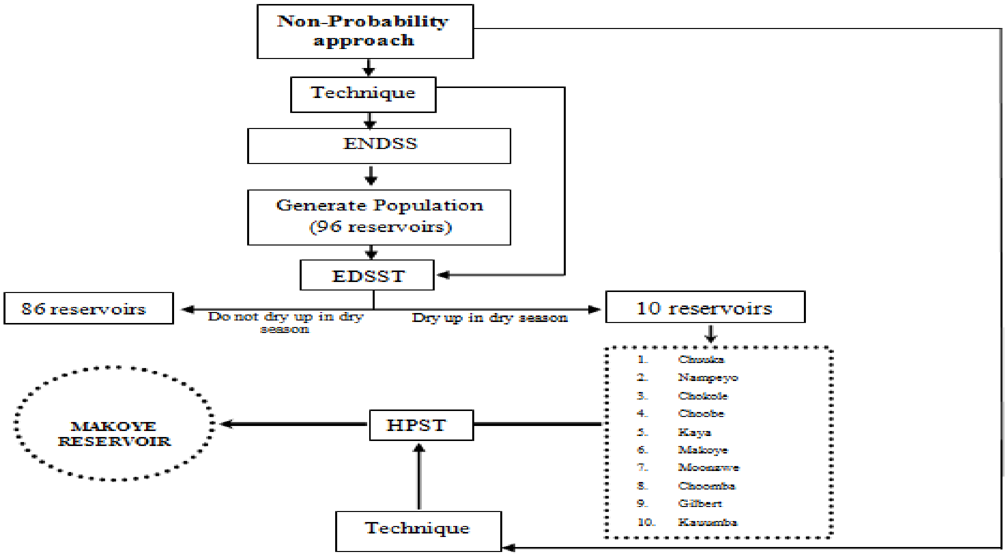
The primary population of small reservoirs in Monze District was 96 (Sichingabula *et al.*, 2014). This population was initially not known to the researcher, in order to generate it. As such the Snowball Sampling Technique (SST) was used. According to Castillo (2009), there are three types of snowball sampling, namely, Linear Snowball Sampling (LSS), Exponential Non-Discriminative Snowball Sampling (ENDSS) and Exponential Discriminative Snowball Sampling (EDSS).

Linear snowball sampling is a process where each identified sample provide reference of only one similar subject or object where a linear chain is created by the completion of desired sample (Gray, 2004). Gray (2004) further defines ENDSS as a non-probability sampling process where an identified member provides reference of at least two similar subjects because of which the size of the sample size grows exponentially and a large population or sample size can be achieved. Castillo (2009) defines EDSS as a process where initially one sample is identified and thereafter provides two references of similar subjects or objects, out of which at least one subjects or object must be active to provide further references and information whilst the other could be none active in providing references.

Applied in context, during reconnaissance survey, a reservoir was being identified together with key informant (its owner or stewards) who would provide information about it. Thereafter, key informants were requested to refer the researcher to other known reservoirs so that the number would increase exponentially. During the generation of the population of reservoirs, the researcher did not discriminate any reservoir that he was referred to because he was looking for a sizeable reservoir, useful to community, and one that would dry up during dry season. Hence, all reservoirs referred to were recorded during reconnaissance survey. After generating 96 small reservoirs through ENDSS during the first and second phases of the reconnaissance survey (2013 to 2014), EDSS was used during the third phase of reconnaissance survey to separate 10 small reservoirs that dry up during dry season (so as to enable the researcher to measure depths of sediment distribution on the reservoir bed) from the 86 that are perennial. At this phase the use of EDSS was essential because it enabled discriminating all perennial reservoirs so as to focus only on those which dry up as the final target population.

EDSS therefore, provided opportunities to discriminate small reservoirs that did not meet the initial criteria (i.e. dry up during dry season) and retain only those that met the initial criteria. Generally, snowball sampling is useful where members of the population have not all been documented and are more difficult to locate than known populations (Spreen, 1992). During reconnaissance survey of reservoirs, the researcher in his own capacity was not likely to have a good list of reservoirs within a specific geographical area. However, as he was visiting different areas to log one or two reservoirs, he usually found that local people knew very well other existing reservoirs, and their owners or caretakers in their vicinity and, how they could be found (Faugier and Sargeant, 1997). The 10 reservoirs that dried during dry season eventually became the final target population of small reservoirs from which Makoye was selected using Homogenous Purposive Sampling Technique (HPST). The reasons for using HPST were that, it allowed selection of a reservoir with specific characteristics (sizeable, dries up during dry season and, suitable for camping activities) needed by the study and researcher (Bryman, 2008). Figure 2 summarizes the sampling process that was used.

Figure 2: Sampling Framework Applied In The Study. Author's Illustration



4.2 Sediment Depth Collection by Digging Pits

Sediment depths data was collected on the 24th of October, 2014 by digging pits about 5-10m apart across the dry bed of the reservoir. The depth was measured using measuring tapes with the aid of ranging poles and the Universal Transverse Mercator (UTM) WGS84 X-Y Coordinates recorded using Garmin GPS-etrex 10 (Table 1). After collecting sediment depths, reservoir perimeter in form of UTM coordinates were collected using Garmin GPS etrex 10. Finally a vertical section of sediment to determine bulk density was obtained using a 40 cm long corer with inner circumference and diameter of 14.5 cm and 7.3 cm, respectively. Collection of sediment core was done on the reservoir bed where the sediment was deepest and, the UTM coordinates were also obtained at the sediment core sampling point. All sediment depth measurements were later entered into Microsoft Excel spread sheet.

4.3 Real Time Sediment Depth and Turbidity Rates Collection Using Sedimeter

Data on real time sedimentation rate was collected using a Sedimeter-SM3A. The Sedimeter measures vertical sedimentation profile - using 36 Optical Backscatter Detectors (OBS) - through the bottom, and calculates the level with resolution of 0.001 mm (Erlingsson, 2016). It was deployed underwater for live recording of sedimentation rates on 3 March 2016 before, but near the peak of 2015/2016 rainy season due to delayed rains caused by the experienced El-Nino event. During the 2016/2017 rainy season, Sedimeter-SM3A was installed on 28 November, 2016 because of early onset of rainy fall triggered by La-Nina event experienced in Zambia. Before deploying it, it was configured through its software installed on the computer. This involved setting up the date and time to start measurement as well as interval of measurement. In this study, hourly interval was adopted to save the battery life. Due to clayish and muddy reservoir bed, the sedimeter was tied to the angle bar which was firmly inserted in the reservoir bed. The Sedimeter-SM3A was installed for about three weeks in 2015/2017 rainy season and about 14 weeks in the 2016/2017 rainy season. It helped to monitor sediment settling rate or accumulation as well as water subsurface turbidity in real time for the first time in Zambia and Africa in general (Erlingsson, 2016). The merit with this equipment is that even though data is not downloaded instantly, it stores it internally for up to over a year during which the data would have been downloaded for analysis.

4.4 Sedimentation Data Collection by Elevation Change Method

In order to estimate sedimentation using the elevation change method, water surface and downstream elevations were collected using Differential Global Position System (DGPS) mounted on the Hydrographic Survey Boat (HSB) (RC-2) that was used to determine maximum depth near the reservoir crest. The dry reservoir bed surface area was determined using volume-area tool in Arc GIS 3D Spatial Analyst. Sedimentation was then determined using formula 1.6 as modified and adapted from Sawunyama (2005) to fit the context of the current study.

4.4 Data Analysis

Sediment depth data was analysed using 3D Spatial Analyst Tools (3DSATs) in ArcGIS 10.3. The input data include sediment depths from pits, geographical coordinates and perimeter of the reservoir. The depth values were assigned with negative numbers so as to display the sediment profile in a basin shape. The reservoir's boundary (perimeter) was converted to points and assigned with a default value of zero. Created reservoir boundary points data were merged with the sediment depth data using the merge tool in ArcGIS 10.3. The next step involved interpolating a continuous raster surface, using raster interpolation under the 3-D Analyst in ArcGIS 10.3. Various interpolation methods, namely, Inverse Distant Weighted (IDW), Kriging, Natural Neighbour and, TIN model were tested and results compared. Using the Area and Volume Tool (AVT) under ArcGIS 10.3 3-D Analyst, Polynomial hydro-hypsometric curves were generated in order to determine Depth-Area and Volume relationships based on the TIN models using Microsoft Excel. The computed area and volume associated with each depth were finally tabulated and displayed graphically. The sediment volume obtained through the above analytical technique was eventually used in analysis of derivative data on long term sedimentation rate, reservoir storage capacity, useful life, reservoir storage capacity, sediment yield, and specific sediment yield based on equation 1.1, 1.2, 1.3, 1.4 and 1.5 provided by Anyekulu *et al*. (2013).

$SR = SV/y$ (1.1

$LE = RSC/SR$ (1.2)

$SY = SV*dBD/y$ (1.3)

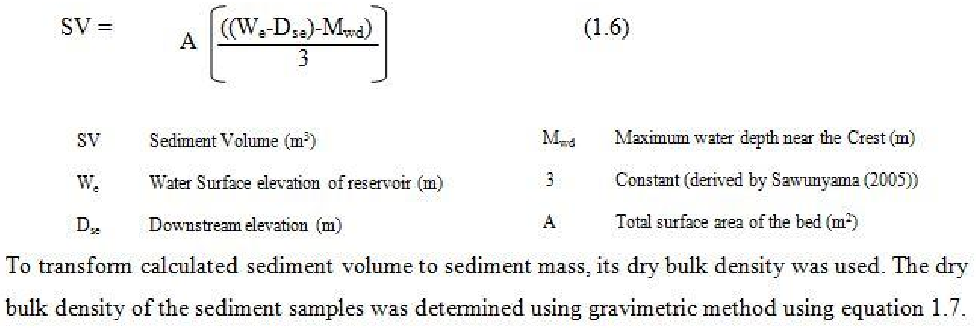
$SSY = SY/A$ (1.4)

$SV = \text{Area} \times \text{Depth}$ (1.5)

Where:

SR	rate of sedimentation (m^3y^{-1})
y	age of reservoir (year)
LE	useful life or life expectancy of the reservoir (year)
RSC	the reservoir storage capacity (m^3)
SY	sediment yield ($t\ y^{-1}$)
dBD	dry bulk density ($t\ m^{-3}$) (sediment dried at 105°C)
SSY	specific Sediment Yield ($t\ km^{-2}\ y^{-1}$)
SV	Sediment Volume (m^3)
A	catchment area (km^2)
Area	the area of contour of sediment thickness
Depth	the thickness of the sediment measured from the pits (m)

In order to compare sediment volume computed using the 3DSATs in GIS Environment, the current study devised a formula 1.6 based on adaptation from original formula Sawunyama (2005). This was useful in the analysis of sedimentation volume by elevation change method.



$$SV = A\left[\frac{((W_e\text{-}D_{se})\text{-}M_{wd})}{3}\right] \quad (1.6)$$

SV	Sediment Volume (m^3)	M_{wd}	Maximum water depth near the Crest (m)
W_e	Water Surface elevation of reservoir (m)	3	Constant (derived by Sawunyama (2005))
D_{se}	Downstream elevation (m)	A	Total surface area of the bed (m^2)

To transform calculated sediment volume to sediment mass, its dry bulk density was used. The dry bulk density of the sediment samples was determined using gravimetric method using equation 1.7.

$$\rho_b = \frac{W_d}{V} \quad (1.7)$$

Where:

ρ_b	Dry bulk density ($Kg\ m^{-3}$)
Wd	Weight of oven-dried soil at 105°C(kg)
V	Volume of core cylinder, (m^3)

To estimate the quantity of water required to saturate the total quantity of sediment in the reservoir, a fully dried up sediment core sample was carefully pounded and thereafter, tightly packed in a transparent container. A known volume of water (0.0023 m^3) was continuously and slowly added to the sediment packed in a container until it got saturated. At this point, the volume of water required to saturate the sample sediment core was determined. Thereafter, the amount of water that would be required to saturate the total quantity of sediment that accumulated in the reservoir was arithmetically determined. Data on real time sediment settling rates was downloaded from the sedimeter SM3A and transferred into Microsoft excel. Thereafter, it was analysed using tables and line graphs in Microsoft excel so as to determine hourly trends of sediment accumulation on reservoir bed.

Since sedimeter also measured hourly turbidity and temperature, trends among settling rates, turbidity and temperature were analysed graphically. The Sedimeter SM3A has two sets of sensors, the top 6 sensors (number 31 to 36) record what is happening in water above the bed, whereas the bottom level sensor 37 records data at the bed or near the bed.

In order to obtain the rates of sedimentation per hour, two consecutive level values computed in the sedimeter software were subtracted in order to determine the difference between them. This value constituted the depth of sedimentation per hour. This was done automatically by creating arithmetic formula in Excel. In order to determine TSS in the sub-water surface vertical column based on turbidity, a sample of water was collected at the same time the sedimeter started real time measurements. Laboratory analysis of turbidity and TSS, among other parameters was done on this sample whose results for turbidity and TSS were 2130 NTU and 3100 mg/l, respectively. Thereafter, these values were used to determine a constant factor that was eventually used to compute TSS for each turbidity record in Sedimeter SM3A.

5. Results

5.1 Reservoir Sediment Quantification

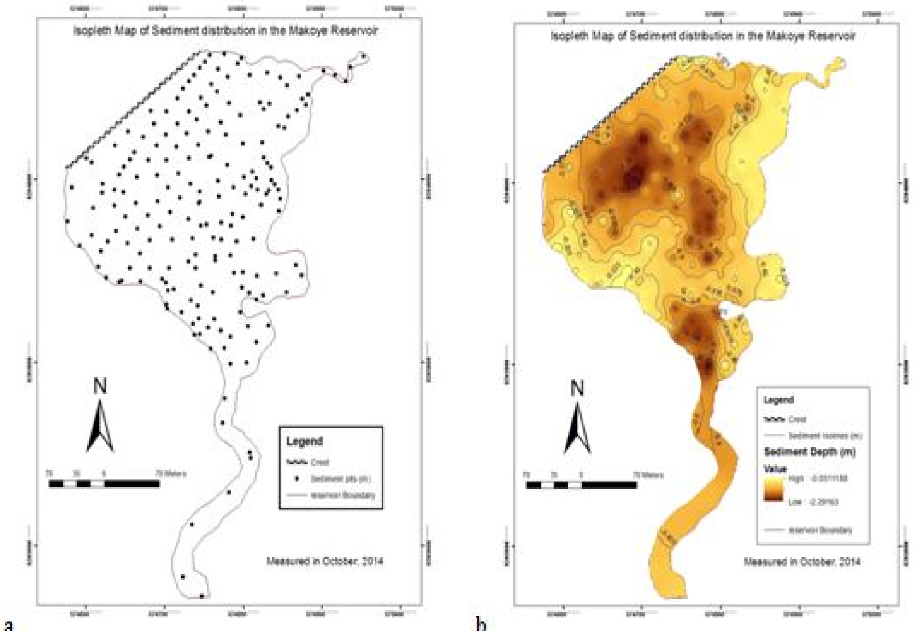
Table 1 shows a sample of collected sediment depths data across the reservoir, the total number of pits was 203 (Figure 3). Table 2 summarizes data of sediment depth, surface area and volumes derived from the IDW, Nearest Neighbour (NN), Triangulated Irregular Network TIN), Krigging (K) and Elevation Change Methods (ECM). Figure 3(a-b) shows the IDW model of sediment distribution across the Makoye reservoir, the sediment isolines were determined at 0.22 m interval

Table 1: Extracted Sample of Sediment Transects Across the Reservoir

Pit no.	Location in UTM		Sediment depth (m)	Elevation (masl) (m)
	X	Y		
1	574591.790	8203927.760	-0.1	1108.360
2	574609.380	8203968.580	-0.1	1107.953
3	574620.200	8203985.290	-0.84	1108.100
4	574636.020	8203988.670	-1.1	1106.552
5	574642.090	8204005.420	-1.2	1106.363
6	574648.490	8204013.820	-1.1	1107.360
7	574655.950	8204022.020	-1.2	1107.030
8	574661.560	8204029.800	-1.2	1107.080
9	574672.560	8204046.350	-1.1	1106.521
10	574686.820	8204060.690	-0.9	1105.892
11	574702.740	8204073.710	-0.9	1107.150
12	574716.400	8204088.480	-0.85	1105.778
13	574723.740	8204098.960	-0.5	1106.918
14	574731.050	8204106.790	-0.8	1106.952

Source: Field measurements (25/10/2014)

Figure 3: Distribution of (A) Sediment Pits And (B) Sediment Depths Across Makoye Reservoir, 25October 2014.



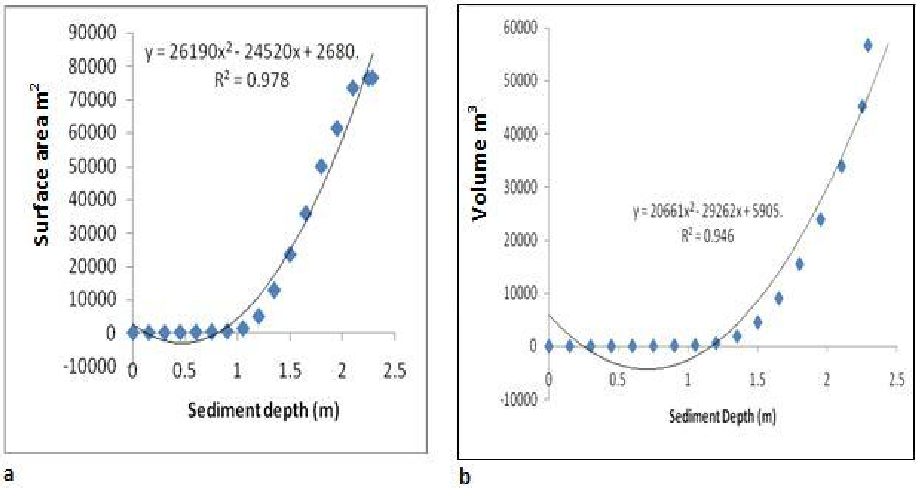
Source: Field Measurements (24th October, 2014).

Table 2: Sediment Volumes of the Makoye Reservoir

ArcGIS Method Techniques								
Inverse Weighted Distance (IDW)			**Nearest Neighbor (NN)**	**Triangulated Irregular Network (TIN)**	**Krigging (K)**	**Average (IDW, NN, TIN, K)**	**ECM (m^3)**	**Average ArcGIS techniques and ECM (m^3)**
Sediment Depth (m)	**Surface Area (m^2)**	**Sediment Volume (m^3)**	**Volume (m^3)**					
2.29	76,437.11	**56,648.09**	**95,905.09**	**95,988.75**	**100,110.62**	**87,163.14**	**79,749.38**	**83,456.26**
2.25	76,239.85	45,188.27						
2.10	73,418.30	33,867.18						
1.95	61,264.18	23,881.51						
1.80	49,846.06	15,490.23						
1.65	35,693.08	9,019.48						
1.50	23,449.25	4,517.49						
1.35	12,727.78	1,880.10						
1.20	4,883.82	591.73						
1.05	1,252.66	197.92						
0.90	395.61	98.35						
0.75	220.80	54.35						
0.60	137.52	27.94						
0.45	80.79	11.93						
0.30	39	3.28						
0.15	6.75	0.12						
0	0	0						

Figure 4 (A-B) Show Depth-Surface Area, Depth-Volume And, Surface Area-Volume Relationships Of Sediment.

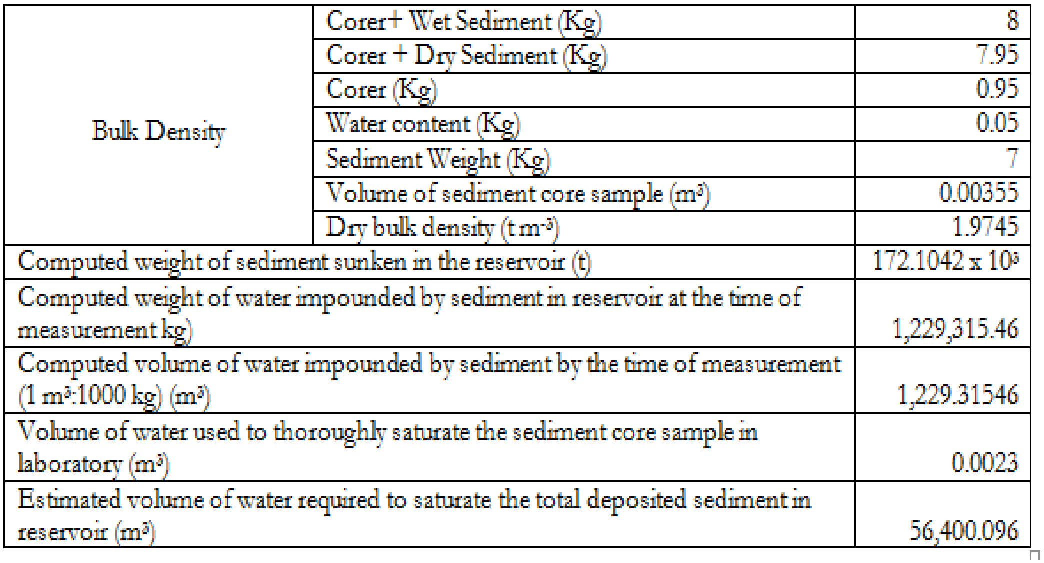
Figure 4: Sediment Hypsometric Graphs Showing (A) Depth- Surface Area Relationship (B) Depth-Volume Relationship of Sediment



Source: Field Measurements (24/10/ 2014).

Table 3 shows the summary of results that emerged from the processing of the bulk density of sediment in the Makoye reservoir. It also shows subsequent findings that emerged as a result of bulk density analysis. The dry bulk density was found to be 1.9745 t/m3.

Table 3: Summary of results that emerged from the processing of the bulk density of sediment

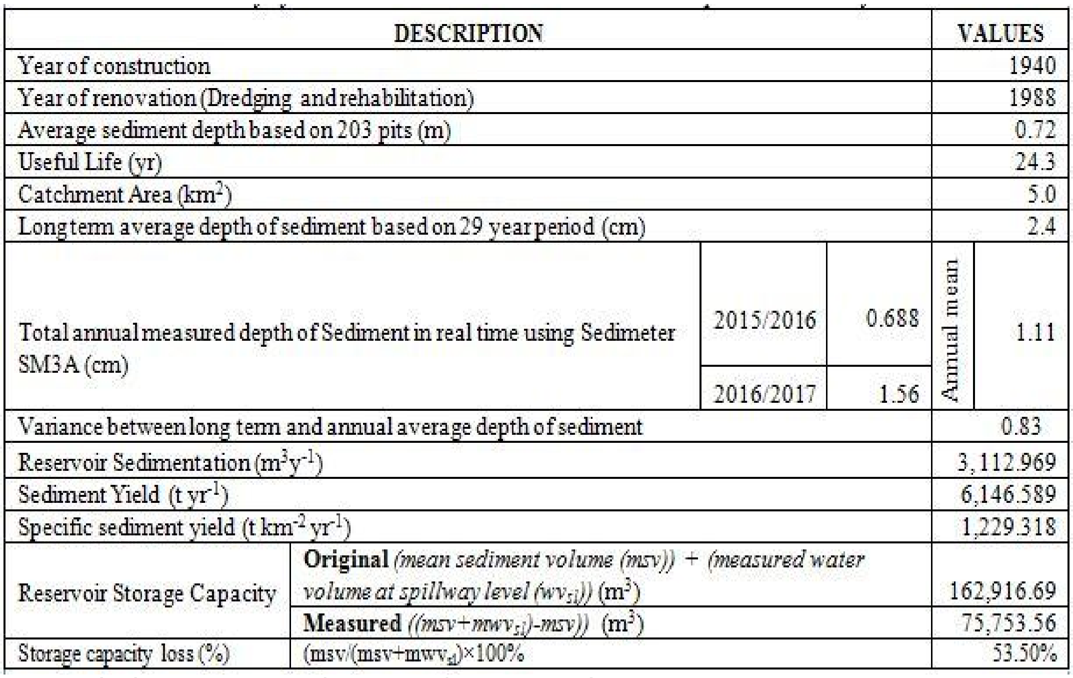


Bulk Density	Corer+ Wet Sediment (Kg)	8
	Corer + Dry Sediment (Kg)	7.95
	Corer (Kg)	0.95
	Water content (Kg)	0.05
	Sediment Weight (Kg)	7
	Volume of sediment core sample (m^3)	0.00355
	Dry bulk density ($t\,m^{-3}$)	1.9745
Computed weight of sediment sunken in the reservoir (t)		172.1042 x 10^3
Computed weight of water impounded by sediment in reservoir at the time of measurement kg)		1,229,315.46
Computed volume of water impounded by sediment by the time of measurement (1 m^3:1000 kg) (m^3)		1,229.31546
Volume of water used to thoroughly saturate the sediment core sample in laboratory (m^3)		0.0023
Estimated volume of water required to saturate the total deposited sediment in reservoir (m^3)		56,400.096

Source: Field Measurements (25/10/ 2014).

Table 4 provides a summary of selected statistics about the Makoye reservoir in terms of its period of construction, renovation and other relevant parameters (useful life, reservoir capacity, storage of construction, renovation and other relevant parameters (useful life, reservoir capacity, storage capacity loss, etc.) worth noting.

Table 4: Summary of Selected Statistics Related to Sedimentation Process in Makoye Reservoir



DESCRIPTION				VALUES
Year of construction				1940
Year of renovation (Dredging and rehabilitation)				1988
Average sediment depth based on 203 pits (m)				0.72
Useful Life (yr)				24.3
Catchment Area (km^2)				5.0
Long term average depth of sediment based on 29 year period (cm)				2.4
Total annual measured depth of Sediment in real time using Sedimeter SM3A (cm)	2015/2016	0.688	Annual mean	1.11
	2016/2017	1.56		
Variance between long term and annual average depth of sediment				0.83
Reservoir Sedimentation (m^{3}y^{-1})				3,112.969
Sediment Yield (t yr^{-1})				6,146.589
Specific sediment yield (t km^{-2} yr^{-1})				1,229.318
Reservoir Storage Capacity	**Original** *(mean sediment volume (msv)) + (measured water volume at spillway level (wv_{sl}))* (m^3)			162,916.69
	Measured *((msv+mwv_{sl})-msv))* (m^3)			75,753.56
Storage capacity loss (%)	(msv/(msv+mwv_{sl})×100%			53.50%

Source: Field Measurements (2014-2016) $*_{sl}$ Spillway level

5.2 Real Time Sedimentation and Turbidity Rates

This section presents results on reservoir sedimentation rates which were measured in real time. Tables 5a-b show two sets of 24 extracts of 309 and 1939 records captured using a Sedimeter SM3A in the 2015/2016 and 2016/2017 rainy seasons, respectively.

Table 5a: Extracts of Real Time Sedimentation for the First 24 Hours in the 2015/2016

NO	TIME	DATE	Sedimentation rate (cm/Hr.)	Mean annual sedimentation rate (cm/hr.)	Turbidity in Top 6 Sedimeter Sensors #31-#36 (NTU) near reservoir Bed	Turbidity in Sensor #37 (NTU) near Water surface
1	14:00:00	4/3/2016	0.01	0.002	8084	41571
2	15:00:00	4/3/2016	0.04	0.002	7967	41375
3	16:00:00	4/3/2016	0.07	0.002	8026	41373
4	17:00:00	4/3/2016	0.04	0.002	8199	41579
5	18:00:00	4/3/2016	0.01	0.002	1223	41937
6	19:00:00	4/3/2016	0.05	0.002	1219	42449
7	20:00:00	4/3/2016	0.03	0.002	1089	42340
8	21:00:00	4/3/2016	0	0.002	1026	42238
9	22:00:00	4/3/2016	0.02	0.002	1055	42236
10	23:00:00	4/3/2016	0.02	0.002	1102	42375
11	0:00:00	5/3/2016	0.01	0.002	1042	42046
12	1:00:00	5/3/2016	0.01	0.002	1040	42207
13	2:00:00	5/3/2016	0.01	0.002	1104	42295
14	3:00:00	5/3/2016	0.02	0.002	1248	42568
15	4:00:00	5/3/2016	0.05	0.002	988	41831
16	5:00:00	5/3/2016	0.07	0.002	1054	41854
17	6:00:00	5/3/2016	0	0.002	1079	41761
18	7:00:00	5/3/2016	0.01	0.002	1158	42145

NO	TIME	DATE	Sedimentation rate (cm/Hr.)	Mean annual sedimentation rate (cm/hr.)	Turbidity in Top 6 Sedimeter Sensors #31-#36 (NTU) near reservoir Bed	Turbidity in Sensor #37 (NTU) near Water surface
19	8:00:00	5/3/2016	0.02	0.002	1135	41941
20	9:00:00	5/3/2016	0.05	0.002	1156	41990
21	10:00:00	5/3/2016	0.01	0.002	1132	42174
22	11:00:00	5/3/2016	0.001	0.002	1242	42208
23	12:00:00	5/3/2016	0	0.002	1163	42038
24	13:00:00	5/3/2016	0.001	0.002	1228	42242

Source: Field measurement using Sedimeter SM3A (2015/2016).

Table 5b: Extracts of Real Time Sedimentation for the First 24 Hours in the 2016/2017

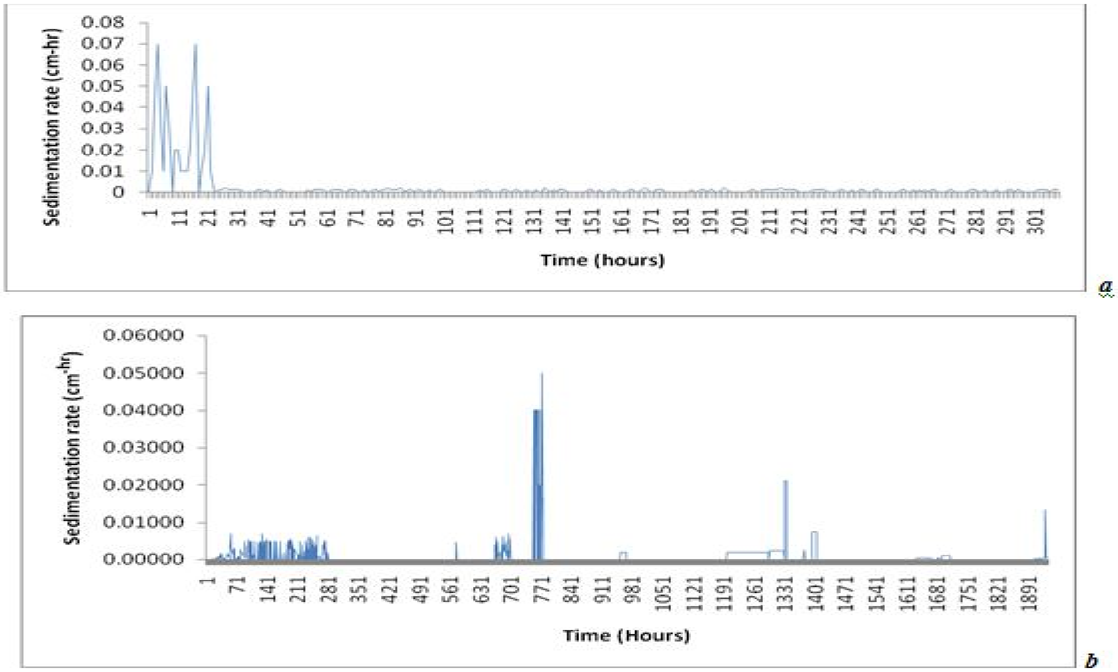
NO	Time	Date	Sedimentation rates (cm/hr.)	Mean sedimentation for the first full day (cm/day)	Annual mean sedimentation (cm/hr.)	Turbidity in Top 6 sensors (31-36) Near reservoir Bed (NTU)	Turbidity in sensor 37 Near Water Surface (NTU)
1	15:00:00	11/28/2016	0.00027	0.01462	0.02652	1224	10759
2	16:00:00	11/28/2016	0.00000	0.01462	0.02652	1221	10709
3	17:00:00	11/28/2016	0.00000	0.01462	0.02652	1238	10661
4	18:00:00	11/28/2016	0.00000	0.01462	0.02652	1228	10462
5	19:00:00	11/28/2016	0.00000	0.01462	0.02652	1243	10456
6	20:00:00	11/28/2016	0.00000	0.01462	0.02652	1230	10433
7	21:00:00	11/28/2016	0.00000	0.01462	0.02652	1234	10412
8	22:00:00	11/28/2016	0.00000	0.01462	0.02652	1224	10440
9	23:00:00	11/28/2016	0.00027	0.01462	0.02652	1228	10418
10	0:00:00	11/29/2016	0.00000	0.01462	0.02652	1232	10429
11	1:00:00	11/29/2016	0.00000	0.01462	0.02652	1230	10435
12	2:00:00	11/29/2016	0.00000	0.01462	0.02652	1228	10459
13	3:00:00	11/29/2016	0.00000	0.01462	0.02652	1222	10422
14	4:00:00	11/29/2016	0.00000	0.01462	0.02652	1229	10444
15	5:00:00	11/29/2016	0.00027	0.01462	0.02652	1222	10422
16	6:00:00	11/29/2016	0.00000	0.01462	0.02652	1227	10507
17	7:00:00	11/29/2016	0.00027	0.01462	0.02652	1262	10646
18	8:00:0	11/29/	0.00000	0.01462	0.02652	1241	10802

	0	2016					
19	9:00:00	11/29/2016	0.00000	0.01462	0.02652	1234	10803
20	10:00:00	11/29/2016	0.00000	0.01462	0.02652	1246	10646
21	11:00:00	11/29/2016	0.00027	0.01462	0.02652	1252	10679
22	12:00:00	11/29/2016	0.00027	0.01462	0.02652	1238	10774
23	13:00:00	11/29/2016	0.00053	0.01462	0.02652	1273	10783
24	14:00:00	11/29/2016	0.34883	0.01462	0.02652	1246	10810

Source: Field measurement using Sedimeter SM3A (2015/2016).

Figure 6a shows hourly rates of sedimentation in the Makoye Reservoir, the highest record for 2015/2016 measurements was 0.07 cm hr^{-1}. During the first two days, the rates were relatively high, but afterwards, the records drastically dropped as shown in Figure 6a most likely due to depletion of sediment in the catchment at peak of rainy season. Figure 6b presents hourly rates of sedimentation in the Makoye Reservoir for the 2016/2017 rainy season. The highest record for this period was 0.05 cm hr^{-1}. Figure 6c-d presents a comparison of trends in turbidity rates in the water near the surface and the waters near or at the reservoir bed. It was evident that turbidity rates were higher near the water surface than near the bottom. This implied that there was large quantity of suspended sediment than that which was settling to the reservoir bed.

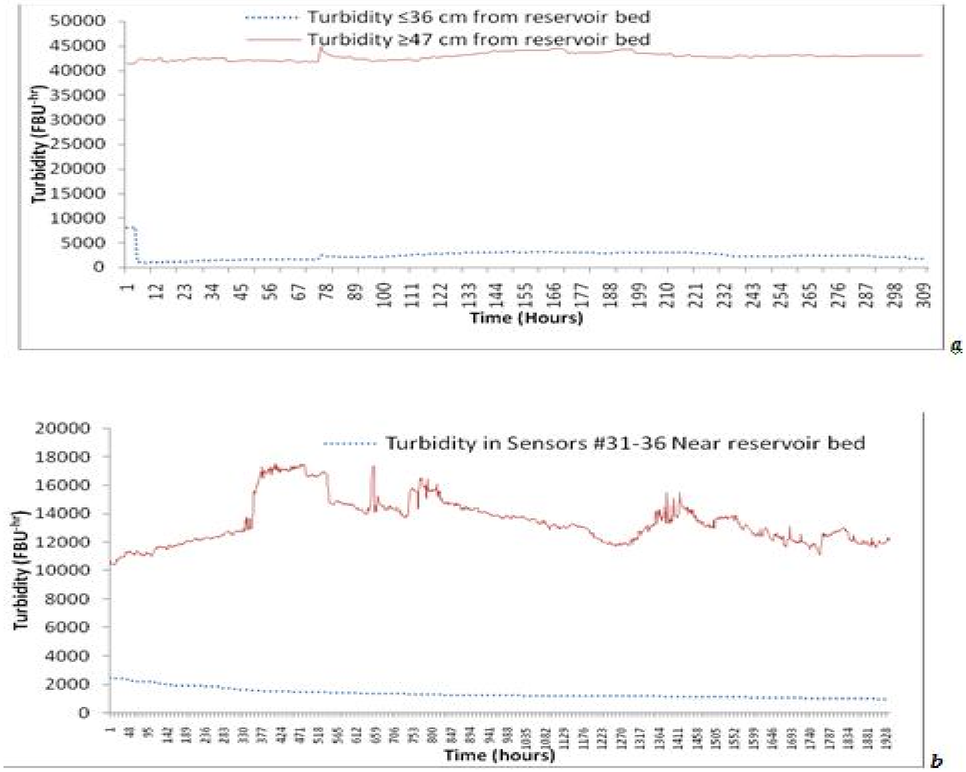
Figure 6: Reservoir sedimentation per hour in the Makoye Reservoir (a) 3- 18 March, 2016 (b) 28/11/2016-17/02/2017



Source: Sedimeter Measurement (2015/2016 and 2016/2017 rainy seasons).

In the 2015/2016 rainy season (Figure 6a), higher readings were only recorded at the beginning of the measurement s, but during the 2016/2017 rainy season, sedimentation readings were fairly spread across the entire period of measurement because the rainfall was fairly well spread in the latter than in the former period as shown in Figure 6a-b. Figure 7a-b shows that hourly turbidity rates near water surface was higher than the water column near the reservoir bed.

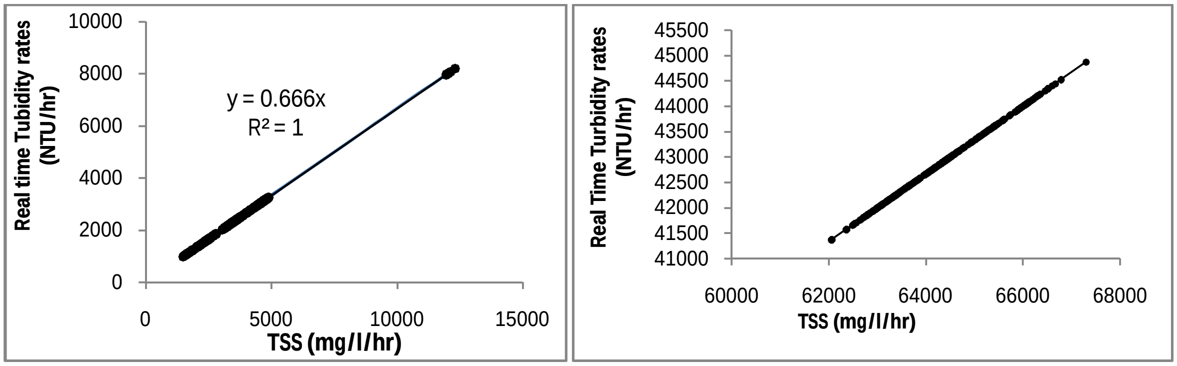
Figure 7: Comparison of Turbidity Trends near Reservoir Bed and Near Water Surface (A) 3- 18 March, 2016 (B) 28/11/2016-17/02/2017



Source: Sedimeter Measurement (2015/2016 and 2016/2017 rainy seasons).

Figure 8 a-b present relationships between Turbidity and Total Suspended Solids (TSS). It is very clear from the graphs that turbidity levels were perfectly influenced by presence of suspended sediment.

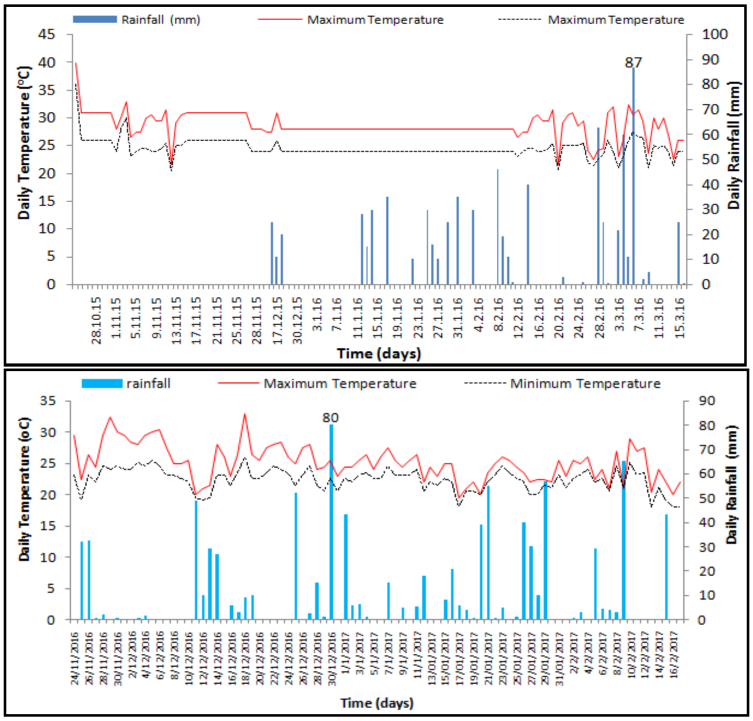
Figure 8: Relationship between TSS and Turbidity in water Column (a) ≤36 cm above the bed (b) ≥47 cm above the bed of the Makoye Reservoir.



Source: Field measurements using sedimeterSM3A (2015/2016)

Figure 9a-b presents the onsite measured daily rainfall and temperature trends for both 2015/2016 and 2016/2017 rainy seasons. The two graphs shows that there was no inter-seasonal homogeneity in rainfall and temperature patterns.

Figure 9: Daily Rainfall and Temperature Trends at Makoye Reservoir (A) 2015/2016 And (B) 2016/2017 Rainy Seasons



Source: Field measurements (2016/2017 rainy season).

6. Discussion of Results

6.1 Sediment volume, Bulk Density and Yields

Figure 3 showed that there was no spatial homogeneity in terms of sediment depths distribution. The depth of sediment on Makoye reservoir varied from 0.1 m to 2.3 m across the surface area of 76,437.11 m^2 with an average sediment volume of 87,163.14 m^3.

This average volume of sediment was computed (based on sediment pits) using different 3D Spatial Analyst tools and the TIN in ArcGIS 10.3. The volume of sediment computed using the ECM was 79,749.38 m^3, this was within acceptable magnitude when compared to the volume computed using ArcGIS tool. The average volume of sediment based on these two methods was 83,456.26 m^3 and, according to earlier observations by Mavima *et al.* (2011), sediment volumes that fall with such magnitude for small reservoirs like Makoye are likely to reduce their optimum function. Hypsometric graphical analysis of sediment depth and volume relationship showed very strong positive non-linear relationship. Evidence in Figure 4b showed that sediment volume sunken at a particular section of the reservoir was strongly dependent on the depth as illustrated by a very strong r^2 values of 0.95. Between 1988 and 2016, Makoye reservoir had impounded 172.104×10^3 tonnes of sediment whose dry bulk density was found to be 1,974.510 kg m^{-3} (Table 3), which entails a high level of compaction per unit volume. Similarly, sediment yield value was estimated at 6,146.59 tyr^{-1} with a specific sediment yield of 1, 229.318 t km^{-2} yr^{-1} (Table 4). The high magnitude of SY and SSY in such a small catchment was attributed to large scale bank cultivation, gully and stream bank erosions as well as grazing within the catchment (Sichingabula, 1997; Mavima *et al*., 2011).

6.2 Sedimentation Rate and Turbidity Rates

The rate of sedimentation was found to be 3,112.97 m^3 yr^{-1} (Table 4), this was higher than the rates of sedimentation in most, if not all reservoir studied by Chomba and Sichingabula (2015) in Lusaka East of Zambia. The rapid rate of sedimentation in the Makoye Reservoir could partly be attributed to its small size. This is supported by McCully (1996:1) who argued that "the rate of reservoir sedimentation depends mainly on the size of a reservoir relative to the amount of sediment flowing into it: a small reservoir on an extremely muddy river will rapidly lose capacity; a large reservoir on a very clear river may take centuries to lose an appreciable amount of storage." The average depth of sediment across the reservoir was found to be 0.72 m (Table 4), based on this value, the long term average depth of sediment was found to be 2.4 cm, which when compared to the short term annual average sediment depth of 1.11 m (computed using Sedimeter SM3A) was higher by 54% which translated into a variance of 0.83 m.

According to Figure 6a-b, the maximum readings of real time sediment depth measurement were at 0.07cm hr^{-1} and 0.05 cm hr^{-1} for 2015/2016 rainy seasons, respectively and, the least records for both seasons were 0.0001 cm hr^{-1} and 0.0003 cm hr^{-1} respectively. According to information under Table 5-b, the total depth of sediment that settled on the Makoye reservoir bed for 309 hours (14 days) in the 2015/2016 rainy season was 0.688cm and, the average settling rate for the entire period was 0.002 cm hr^{-1}. Since the period of measurement for 2015/2016 rainy season was short due to poor rainfall caused by El-Nino (ZMD, 2016), there was no significant settling of sediment on the reservoir bed and, results could not be generalized to the whole rainy season as they were only restricted to individual rainfall events. Rajtantra (2013) confirms that rainfall does not only increase sediment yields, but also contributes significantly to reservoir sedimentation. Such statistics as shown in Table 5a inherently entail that significant erosion, transportation and deposition had already occurred prior to real time measurement of sedimentation. , in fact, on site measurements of daily rainfall show that over 551 mm of rainfall had already occurred prior to measurements therefore, these measurements are only confined to that specific period of measurement. By the time the recordings were done, only two major storms (60 mm on the 4 of March, 2016 and 87 mm on the 6 March, 2016) occurred (Figure 9a).

Nonetheless, for the 2016/2017 period, sufficient rainfall was received due to La-Nina phenomenon which is usually associated with heavy rainfall and flash floods (ZMD, 2016) (Figure 9b). The total annual depth of sediment deposited on the Makoye Reservoir bed in real time was 1.56 cm, whereas, the annual average rate of sediment accumulation was 0.001 cm hr^{-1}. In 2016/2017 season, sedimentation readings were fairly spread across the entire period of measurement as compared to the 2015/2016 rainy season and, this could be linked to a well spread distribution of rainfall in the 2016/2017 rainy season. The total depth of sediment deposited for both seasons was 2.23 cm, this was almost the same as the 2.5 cm long term average depth computed based on average depth of sediment pits divided by the current age of the reservoir. However, as already indicated, annual average was still smaller than the long term average. Ajith (2016) adds that, the rate of sediment settling to the bottom could be delayed by the size and mass of sediment suspended in water. This perhaps explains why the turbidity levels in waters above 47 cm from the reservoir bed were very high as shown in Figure 6c and Figure 6d. Turbidity is the amount of suspended solids in water (Paaijmans *et al.,* 2008). Water turbidity was very high for 2015/2016 season, the maximum and minimum readings were 44865 and 41373 NTU, respectively.

The average turbidity record was at 41373 NTU, which means that most of the sediment in water were still in suspension intercepting a lot of incoming light. Paaijmans *et al* (2008) has clearly documented how an increase in turbidity decreases near water surface temperature.

The general conclusion on the results in Figure 7a-b is that, there was a high level of turbidity in water column (≥47 cm) above reservoir bed than there was in the water column below 47 cm. This indicated slow settling rates of suspended sediment (clay and silt) to the bed as partly demonstrated by a perfect positive linear relationship (r^2 1) between TSS and turbidity in Figure 8a-b for 2015/2016 rainy season. In the 2015/2016 rainy season, the real time maximum and minimum turbidity rates for the water column ≤36 cm were 8199 and 988 NTU, respectively. The average turbidity rate within this column was 2452.43 NTU hr^{-1}. As for the water column ≥47 cm above reservoir bed, the maximum turbidity rate was 44865 NTU hr^{-1} whereas, the minimum value was at 41373 NTU hr^{-1}. The average turbidity rate was 42867.43 NTU hr^{-1}. In the 2016/2017 rainy season, similar trends were noted, but the turbidity rates near water surface were not as high as those recorded during the previous rainy season. The maximum, minimum and average turbidity rates near the water surface (≥47 cm) were 17544 NTU hr^{-1}, 10412 NTU hr^{-1} and 13464.04 NTU hr^{-1}, respectively. Meanwhile the turbidity rates near the reservoir bed (≤36 cm from the bed) were extremely low compared to the previous season's readings. Maximum and minimum readings were 2472 NTU hr^{-1} and 942 NTU hr^{-1} respectively, the average was computed at 1344.61 NTU hr^{-1}. According to Lu *et al.* (2013), sediment such as clay has particle diameter of <0.002 mm, whereas, silt sediment has the particle size of between 0.002 mm and 0.06 mm. Since the suspended sediment in the Makoye reservoir was mainly characterized by clay and silt, it can safely be argued that the sluggish rate of settling rate was due to small particle size of the suspended sediment, which was very less dense to quickly settle on the bed and, hence, the spiked levels of turbidity.

Such levels of turbidity in water were far beyond the acceptable standards of <1000 NTU (FAO, 1978) for livestock watering. High turbidity levels have health implications on livestock, which MLF (2016) already suspected to have led to diarrhea sicknesses and, even death of some animals in Njola where Makoye reservoir is found. The reality found on the ground makes the FAO standards somehow unrealistic in this spatial context because animal were still drinking the same water, which when screened through FAO environmental standards for livestock (<1000 NTU), would be over 4 times unsuitable for livestock use. This is the reason why the Context Bound Maximum Permissible Limit (BMPL) is being proposed in the current study and, this could be determined by Zambia Bureau of Standards and MLF.

6.3 Reservoir Capacity and Useful Life

The quantity of sediment loaded in the Makoye reservoir reduced its original reservoir capacity (162,916.698 m^3) by 53.5% since 1988 when the reservoir was renovated. This means that only 46.5% of reservoir storage capacity was available and, when the water gets to reservoir's full capacity, about 79,460.44 m^3 of water is wasted over the spill way, with possible risks of causing crop and household flooding downstream. By 2016, the useful life of Makoye reservoir stood at 24 year, but given the rapid rate at which sedimentation was determined, the life span might be less than the projected duration. Further laboratory analysis revealed that the total load of sediment deposited in the Makoye reservoir absorbed an estimated 1,229.32 m^3 (Table 3). This water would have been useful for domestic use and livestock, had it not been trapped by sediment. Using formula 1.8 as devised for this study, about 56,400 m^3 of water would be required to saturate 87,163.14 m^3 of dry sediment in Makoye reservoir before water could start accumulating for livestock and domestic purposes.

$$V_{wss} = V_{tsr}\left(\frac{V_{dss}}{V_{scs}}\right) \qquad (1.8)$$

Where:

V_{wss}	Estimated volume of water required to saturate total volume of sediment in a reservoir (m^3)
V_{tsr}	Total measured volume of sediment in the reservoir (m^3)
V_{dss}	Volume of water required to saturate dry sediment core sample (m^3)
V_{scs}	Volume of sediment core sample (m^3)

7. Conclusion

The study concluded that sedimentation is a serious problem in the Makoye Reservoir and, may lead to loss of its optimum function, extinction of storage capacity and, threatened water security as the useful life of the reservoir was projected to only last for the next 24 years. The reservoir had been silting at a significant rate of 3,112.97 m^3 yr^{-1} leading to average accumulation of 87,163 m^3. This average volume of sediment was computed (based on sediment pits) using different 3D Spatial Analyst tools and the TIN in ArcGIS 10.3. The volume of sediment computed using the Elevation difference Method (ECM) was 79,749.38 m^3 and, it was found to be within acceptable magnitude when compared to the volume computed based on sediment pits. The average volume of sediment based on these two methods was 83,456.26 m^3 and, this was found to have reduced the reservoir's storage capacity by 53.5%.

Results from Sedimeter SM3A showed that a total depth of 0.688cm of sediment had accumulated during a period of 309 hours in the 2015/2016 rainy season, however, during the 2016/2017 rainy season, 1.56 cm depth of sediment had accumulated giving rise to biannual average total of 1.11 cm. Based on sediment coring, the long term average depth of sediment in the Makoye reservoir was found to be 2.4 cm, but the short term annual average depth determined using Sedimeter SM3A was 1.11 cm giving rise to 54% difference between the two averages. Through the use of real time sedimentation measurement, it was determined that 0.688 cm of sediment depth had accumulated during a period of 309 hours (14 days) , showing a very high deposition rate for few rainfall events. In the 2016/2017 (November, 2016 to mid February, 2017), the total real time depth of sediment was 1.56 cm, this was slightly lower than the long term (29-year period) average depth of 2.4 cm.

Biannual sum of real time sediment depths (2.23 cm) was closer to the long term average, but the mean was found to be lower although it was within acceptable magnitude. In a nutshell, the overall picture of sedimentation in Makoye reservoir reached alarming levels given that the reservoir capacity had been highly compromised such that that even a single storm event (for example during (2016/2017) was almost able to fill up the reservoir to full capacity. This posed a serious threat to water security within the immediate catchment of Makoye reservoir given that there was already an estimated 79,460.44 m^3 of water that was just going to waste through the spillway. The findings of this study may be of interest to diverse communities of water and sediment scientists especially those interested in fluvial-geomorphology of small reservoir catchments that have similar characteristics as Makoye reservoir. Some methodological approaches such as ECM and real time measurement of sedimentation were quite new and, are worth testing in other geographical regions.

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